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The Er:YAG Laser in Ear Surgery: First Clinical Results

Dethard Nagel, MD*

Kuranstalten und Forschungsinstitute Bad Lippspringe GmbH,
Bad Lippspringe, Germany

Background and Objective: **The goal of this study was to gain experiences about the possibilities and limits of the Er:YAG laser for ear operations.**
Study Design/Patients and Methods: **Eighty-three ear operations were performed with the aid of an Er:YAG laser: 32 stapedotomies, 15 tympanoplasties type III, 10 tympanoplasties type I, 18 ear operations in cholesteatoma, and 8 removals of hyperostosis in the outer ear canal.**
Results: **The Er:YAG laser facilitated stapedotomies and removal of hyperostosis from the outer ear canal. In cases of beginning cholesteatoma, the Er:YAG laser allowed matrix removal of the ear ossicles left in situ. Furthermore, in tympanoplasty it was possible to achieve an osteosynthesis of the auditory ossicles, which was done for the first time during this study. No hearing loss attributable to laser dose was found during postoperative hearing tests.**
Conclusion: **The Er:YAG laser seems to become a useful tool in middle ear surgery. Lasers Surg. Med. 21:79–87, 1997.**

Key words: **auditory ossicles; cholesteatoma; ear canal; hyperostosis; middle ear surgery; osteosynthesis; stapedotomy; tympanoplasty**

INTRODUCTION

The Er:YAG (erbium yttrium aluminum garnet) laser is particularly well suited for microsurgery in the middle ear [1]. According to its physical properties, this laser reaches its highest degree of effectiveness in the infrared range of the emitted light at a wavelength of 2,940 nm, the peak absorption rate for light in water [1,2]. Unlike all other lasers used so far in middle ear surgery—CO_2, KTP (potassium-titanyl-phosphate), Ho:YAG (holmium-yttrium-aluminum-garnet), Argon, etc.), tissue ablation is achieved through explosive rather than thermal effects [3]. The light in the application area of the laser is predominantly absorbed by intra- and extracellular water molecules in the tissue, and it changes their aggregate state from liquid to vapor within microseconds, i.e., tissue in the area of action, especially bone, vaporizes explosively. Structures adjacent to the laser operative field absorb only very little thermal energy. Therefore, in these neighboring areas there are almost no carbonization and coagulation effects [4]. After 3 years of extensive studies in the laboratory for potential damage in a guinea pig model, acoustic traumatisation by the application of the Er:YAG laser in the ear canal, on the tympanic membrane, and the middle ear bones could largely be excluded [5]. After presentation of these results to the Ethical Committee of the University of Ulm and their approval, clinical testing with human ear surgery commenced in 1994.

MATERIALS AND METHODS

Eighty-three operations were performed with the aid of an Er:YAG laser in 71 patients (33 women, 38 men, ages 7–64 years). An Er:YAG

*Correspondence to: Dr. med. Dethard Nagel, Klinik für Hals-Nasen-Ohrenkrankheiten, Kopf-und Halschirugie Karl Hansen Klinik, Postfach 1280, D-33167 Bad Lippspringe, Germany

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laser was provided by Carl Zeiss Oberkochen for a clinical research program. It was successfully adapted to an operating microscope (OPMI 111) delivering a laser beam precisely focused to a spot diameter of 0.2 mm at 25 cm focal length. A diode laser was used for aiming and focusing.

By optimized focusing, tissue vaporization could be achieved at pulse energies exceeding 12 mJ. With this amount of energy, tissue is removed to ~ 0.1 mm in width. The depth depends on the type of tissue, with a range from ~ 0.01 mm in bone to 0.025–0.05 mm in connective tissue and epithelial layer [3]. Tissue ablation increases in width and depth in an almost linear manner with increasing pulse energy. The maximum pulse energy of 100 mJ tested here produced a crater of ~ 0.4 mm in diameter and ~ 0.7 mm in depth in bone.

The laser pulse duration was held constant at 0.25 msec during clinical application. This pulse duration has also been tested in the preliminary animal studies by comparing audiograms before and after laser application in 44 anesthetized guinea pigs. These examination of the animals was carried out on the one hand via the cochlear microphonics, and on the other hand via the BERA (brainstem evoked response audiometry) threshold [5].

The beam profile of the Er:YAG laser corresponding to a multimode emission had an almost rectangular shape. The pulse repetition rate has been set to 2 Hz because at this rate the surgeon has sufficient time to react, e.g., to switch off the laser in case the beam accidentally moves off its target. At this repetition rate, “larger” areas can still be removed efficiently.

The total amount of tissue removed depends mainly on spot size and energy density. However, depending on the type of tissue the laser is directed at and depending of the amount of water in the tissue, the ablation varies somewhat in strength even if laser energy is kept constant. To some degree the angle with which the laser beam hits the tissue also influences tissue ablation, and at angles below 45°, the target area increases in size to such an extent that the energy density is no longer sufficient. It also should be noted that normally no tissue is removed if water, ichor, or blood has accumulated in the target area of the laser. However, dried-out areas lead to amplification of the otherwise only mild thermal effects in adjacent structures.

The spot diameter determines, ceteris paribus, the energy density of the Er:YAG laser in the tissue and thus ablation depth and pattern. For most Er:YAG laser applications (such as bone ablation, creating small holes in the auditory ossicles, perforation of the footplate and cutting the crurae of the stapes and ablation of the cholesteatoma matrix from the ear ossicles) minimum spot diameter is recommended to put the micro-surgical advantages of the Er:YAG laser to optimum use. Only if the goal is a whole surface area epithelium removal, an increase in the spot diameter can be advantageous. This can be achieved through controlled defocusing of the laser beam. The energy transferred will have to increase proportional to the increase in spot size.

RESULTS

Surgical Procedures

Stapedotomy. Between January 1994 and May 1995, the Er:YAG laser has been used in 32 stapedotomies as an operative aide to the surgeon for perforation of the footplate and to cutting the ligament of the stapes muscle and the crurae of the stapes.

Footplate perforation. With the Er:YAG laser, the inner ear can be opened by contactless perforation of the footplate. The Er:YAG laser has been used successfully for perforation of the footplate on 32 patients with otosclerosis. Generally, 3–8 laser pulses of 25 mJ energy each precisely focused and accurately deliverd at an angle of 70–90° proved to be sufficient for perforations with a diameter of 0.4–0.5 mm, which allows optimal fitting of the artificial stapes prosthesis.

Severance of the crurae stapedis. Contactless severance of the crurae stapedis is also possible with the Er:YAG laser. On average, 5–11 × 25 mJ pulses with optimal focus were necessary to cut the crurae depending on their thickness.

Ligament severance of the stapes muscle. Five to ten Er:YAG laser pulses of 25 mJ easily cut the ligament of the stapes muscle, but here conventional techniques work just as well.

Tympanoplasty Type I. Ten tympanoplasties Type I between January 1994 and May 1995 have been carried out with the aid of the Er:YAG laser. It is possible to use the Er:YAG laser to cut the perforation edge of the tympanic membrane precisely. Due to the characteristics of explosive tissue ablation, no coagulation of the microvessels of the tympanic membrane occur. Atrophic leftovers of the tympanic membrane, which are easily destroyed using conventional cutting instruments, can be preserved better with the Er:YAG

laser technique. Single pulses of 25 mJ with optimal focus proved best results. In all cases, the subsequent healing process showed no complications.

Tympanoplasty Type III. Fifteen tympanoplasties Type III have been carried out between January 1994 and April 1995. The Er:YAG laser was used for stabilization of the ossicles in the form of quasi osteosynthetic linkages. With ideal focus, laser pulses with an energy from 225–25,000 mJ (9 × 25–500 × 50 mJ) have been used.

For the first time the Er:YAG laser opens up the possibility of osteosynthetically linking the ossicles for the reconstruction of middle ears. It enables the surgeon to pierce cylindrical holes into the auditory ossicles in situ with a well-defined caliber of 0.2 mm and a length of up to 8 mm. Thus a wire can be inserted for osteosynthesis. For the first time, the surgeon can built up a stable connection of the ossicles, which enables a pull-strength to the stapes during acoustic transmission in the middle ear with the corresponding reduced impedance and thus improved acoustic transmission.

Removal of hyperostosis in the ear canal. Eight patients with hyperostosis have been operated between January 1994 and February 1995 to remove the hyperostosis and to widen the ear canal. In all cases the maximum energy dose of 25,000 mJ was used. The Er:YAG laser is well suited for the removal of bone tissue. It has been used for the removal of hyperostotic bone in close proximity to the tympanic membrane. The obvious danger that the tympanic membrane may be touched by a drill, leading to acoustic trauma of the inner ear [6], can thus be avoided. To remove the hyperostosis off the ear canal, a pulse energy of 50–100 mJ and a pulse frequency of 2 Hz is recommended.

Cholesteatoma. Eighteen patients with cholesteatoma have been operated with the aid of the Er:YAG laser. It was used as well to remove the cholesteatoma matrix from the ear ossicles as for preparing the ossicles for middle ear reconstruction. Since the laser allows this without mechanical contact, the ossicles can remain in situ. If the beginning cholesteatoma has not yet destroyed the ossicles, normal hearing can be restored by this technique. Conventional techniques usually force the surgeon to disconnect the ossicles to remove the cholesteatoma and thus prevent inner ear hearing damage. The removal of the cholesteatoma matrix of the in situ remaining ossicles worked best with precisely focused single pulses of 25–50 mJ. Total energy doses of 225–25,000 mJ were needed. In future probably it will be possible to remove matrix parts that presently cannot be reached directly by the Er:YAG laser beam, with a mirror currently under development.

Hearing

Stapedotomy (otosclerosis). Figure 1a,b shows the hearing results of the 32 Er:YAG laser aided stapedotomies. Mean hearing gain is 18 dB, median is also 18 dB over all frequencies. The comparison of (a) and (b) in Figure 1 shows that the hearing gain is significantly higher in the lower frequency bands of .5–2 kHz corresponding to the higher air bone gap at these frequencies. Case 8 shows almost no postoperative improvement. It was the second revision of previous alio loco performed operations, where the otosclerosis had refixed the initially implanted prosthesis. It could successfully be removed with the Er:YAG laser, but a sufficient free-moving ability of the new implanted prosthesis could not be achieved. Despite the necessary high total energy dose of 85 × 25 mJ used during the opening of the closed oval niche, no hearing loss was found during postoperative examination of the bone conduction threshold.

Case 9 developed a fistula of the perilymphatic fluid and problems with the sense of balance 14 days after the stapedotomy. The immediate postoperative bone conduction threshold was unchanged but dropped in subsequent trials. The fistula was probably caused by the untouched epithelium of the footplate, which in this case has not been removed before the Er:YAG laser application was performed. In consequence, the connective tissue transplant placed around the stapes prosthesis to prevent the fistula could not heal on. This was discovered during the revision operation. In all subsequent operations, the epithelium has been removed with a needle from the footplate prior to laser application. No fistulas have been observed since.

The frequencies widely accepted as most sensitive to traumatisation of the inner ear are 4 and 8 kHz. Therefore, derived from postoperative hearing tests, these frequencies were chosen to look for signs of acoustic trauma. The statistical evaluation of the pre- and postoperative bone conduction difference at all tested frequencies (.5, 1, 2, 4, 8 kHz) demonstrates a distribution that is approximately normal as shown in Figure 1c, in-

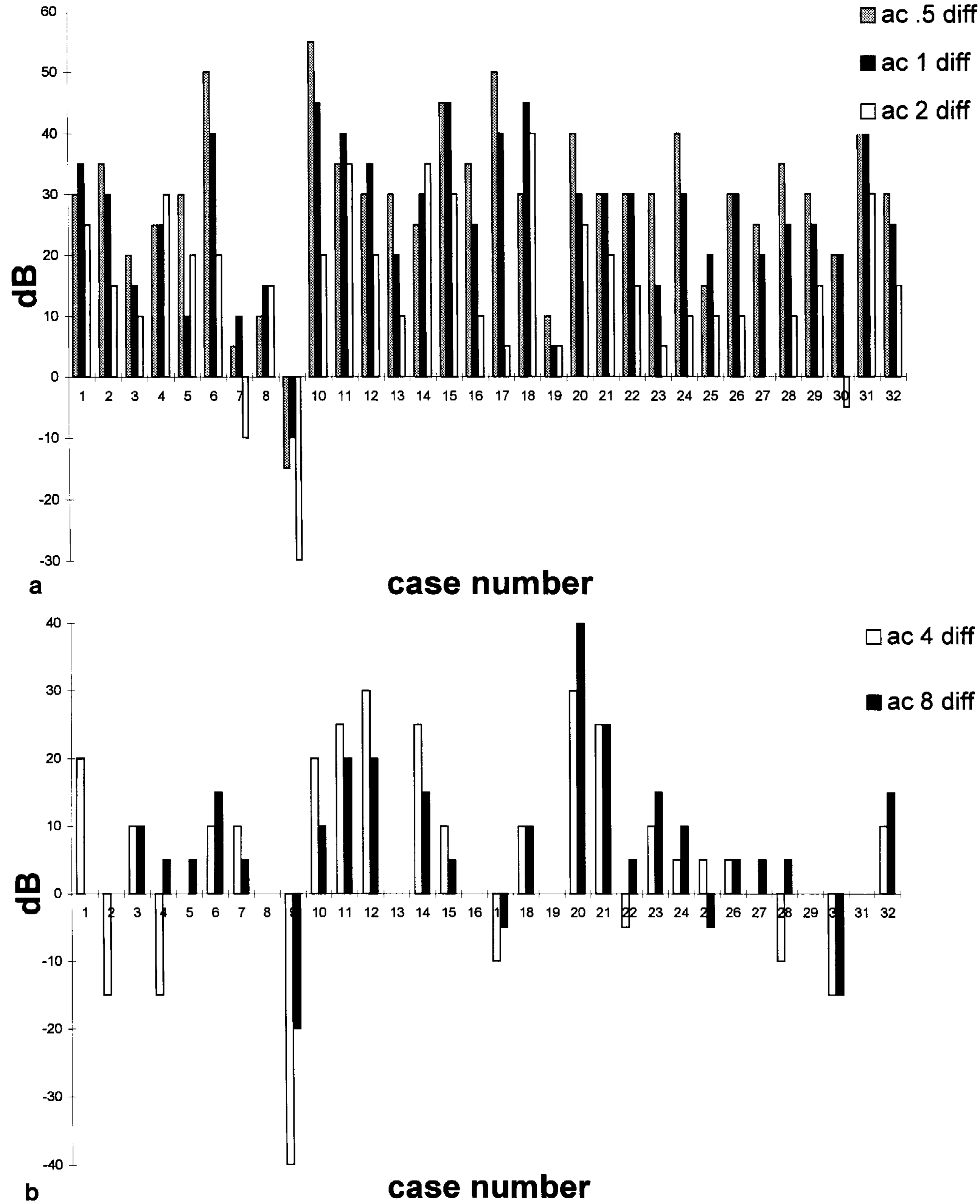

Fig. 1. (**a** and **b**) Er:YAG laser-aided stapedotomies: Hearing gain. Results are given in dB difference between preoperative and postoperative air conduction threshold at .5, 1, 2, 4, and 8 kHz. (**c**) Er:YAG laser-aided stapedotomies: Histogram of bone conduction threshold difference at .5, 1, 2, 4, and 8 kHz, showing an approximately normal distribution.

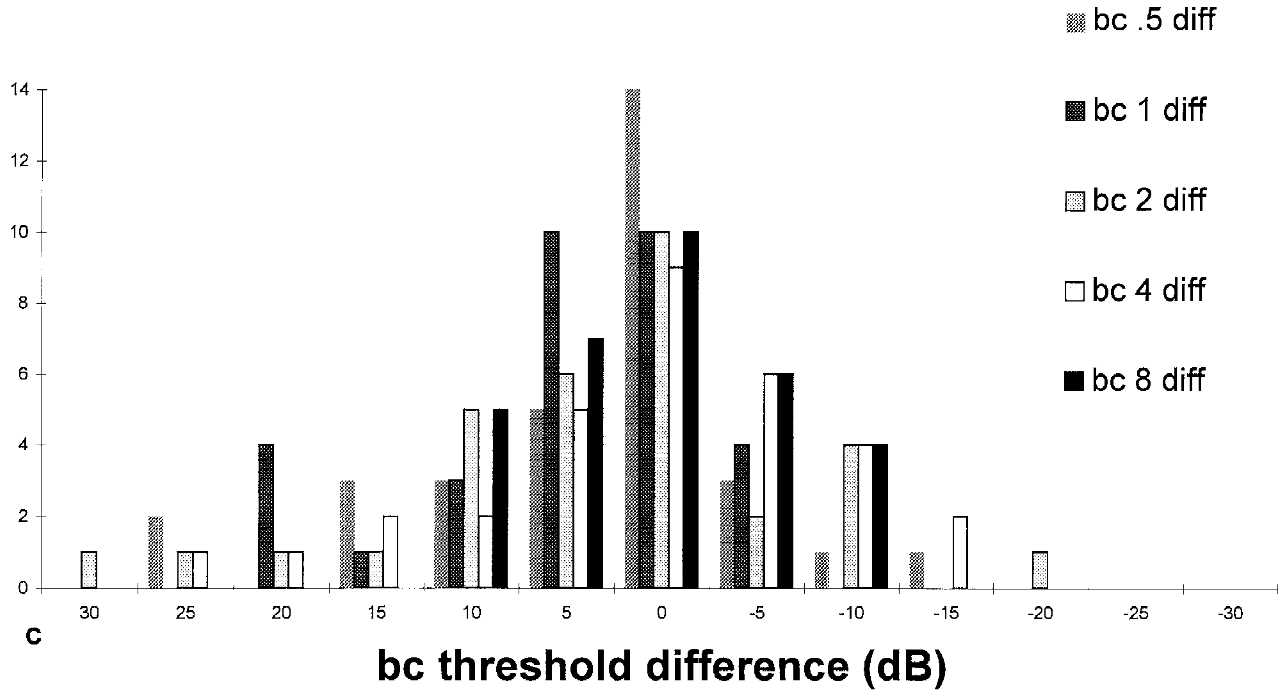

Fig. 1c.

dicating that during the stapedotomy, no systematic inner ear hearing damage occurred during laser application with the opening of the vestibulum or during the insertion of the stapes prosthesis, the most delicate acts in stapedotomy.

Tympanoplasty Type I. The ten tympanoplasties Type I cases showed no hearing loss of bone conduction, which possibly could emerge out from acoustic trauma of the inner ear by the Er: YAG laser application. Patients who were operated with local anesthesia and with normal hearing of the inner ear found the noise level of the Er:YAG laser as intense as loud speech. None of the locally anaesthetized patients showed any signs of discomfort, such as repulsive movements even by unannounced Er:YAG laser applications. In all cases, the tympanic membrane defects could be sealed successfully. In ambulant controls during the following 2 years, no signs of translocation of epithelium such as cholesteatoma in the middle ear or the ear canal could be found. This result should encourage further tympanoplasties Type I with the aid of the Er:YAG laser, but the number of cases as yet seems too small to draw statistically valid conclusions.

Tympanoplasty Type III. Out of 15 tympanoplasties Type III, five patients showed a postoperative permanently lowered bone conduction threshold at 4 kHz (3 patients at 8 kHz) of a maximum of 5–10 dB compared to preoperative audio tests. In all other cases the bone conduction threshold was at least unchanged at 4 and 8 kHz. Six patients even showed an improved bone conduction threshold of 5–15 dB at 4 kHz (4 patients at 8 kHz). The postoperative bone conduction threshold showed no correlation to the total laser dose. No sign of acoustic damage of the inner ear through the Er:YAG laser application could be found, but the numbers of cases were too small to draw statistically relevant conclusions. The differences in the 4 kHz and 8 kHz range of the bone conduction threshold thus appear to be normal random fluctuations during audio tests, since the bone conduction threshold has larger recognized fluctuation bands (plus/minus 10 dB) than the air conduction threshold (plus/minus 5 dB).

Removal of hyperostosis. Between January 1994 and February 1995, eight patients with auditory canal hyperostosis were operated to remove the hyperostosis and widen the auditory canal. The hyperostosis was largely removed with a drill. The Er:YAG laser was applied only to remove the remaining bone edges in close proximity to the tympanic membrane. In all cases the maximum laser dose of 25,000 mJ was used (considered safe from animal testing results) [5]. The comparison of pre- and postoperative bone conduction threshold by audiogram showed no case

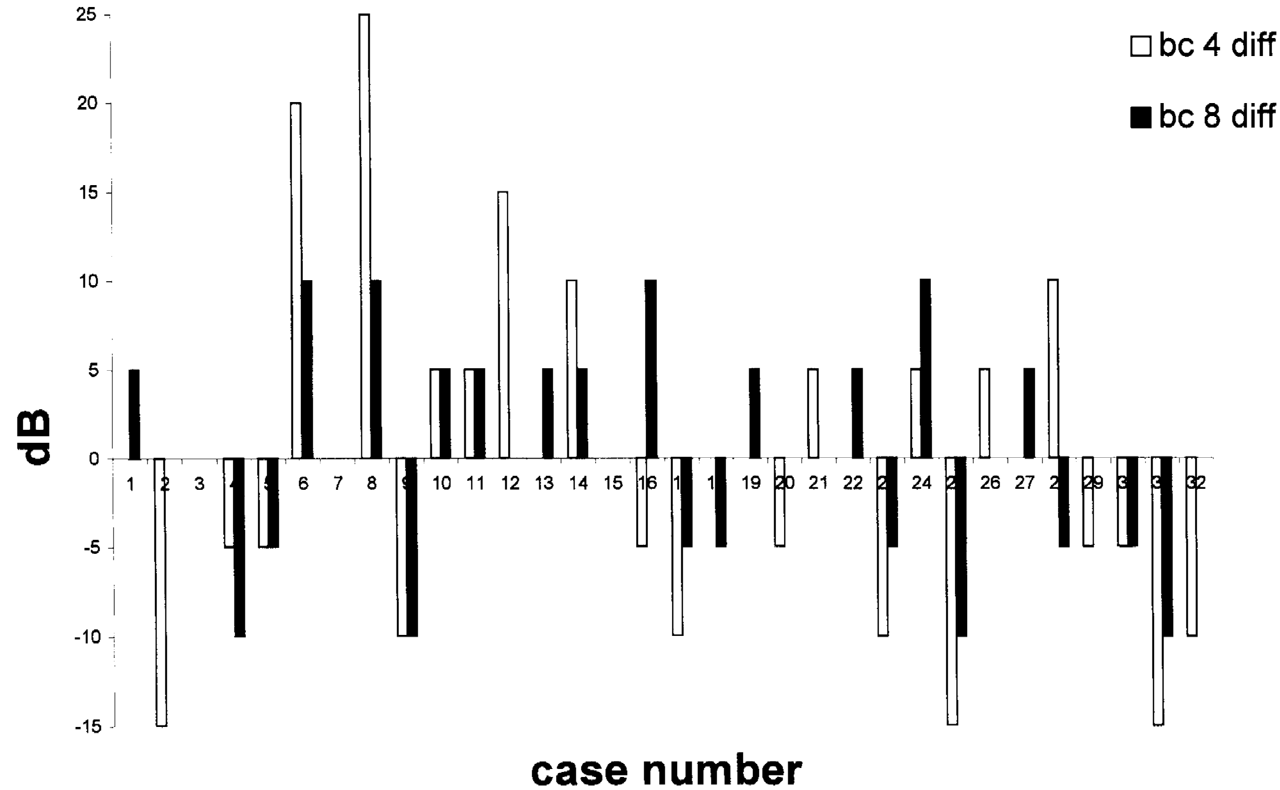

Fig. 2. Er:YAG laser aided stapedotomies: Difference of pre- and postoperative bone conduction threshold at 4 and 8 kHz.

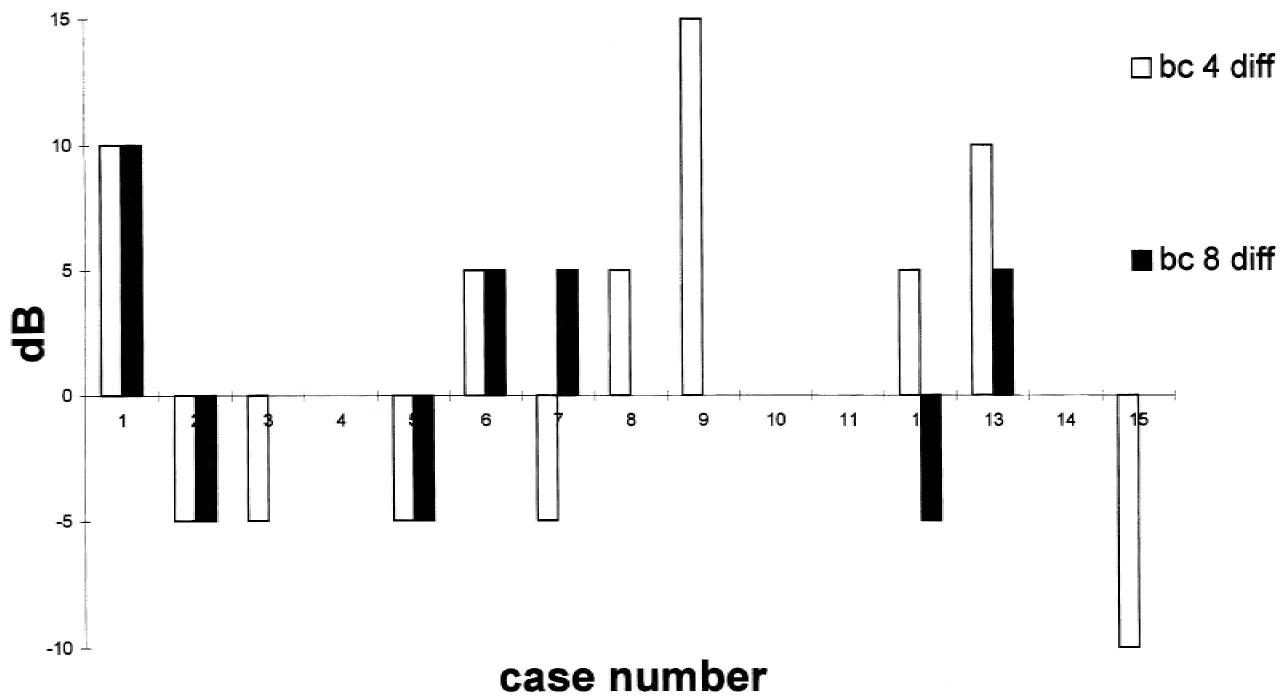

Fig. 3. Er:YAG laser-aided tympanoplasties type III: Difference of the pre- and postoperative bone conduction threshold at 4 and 8 kHz.

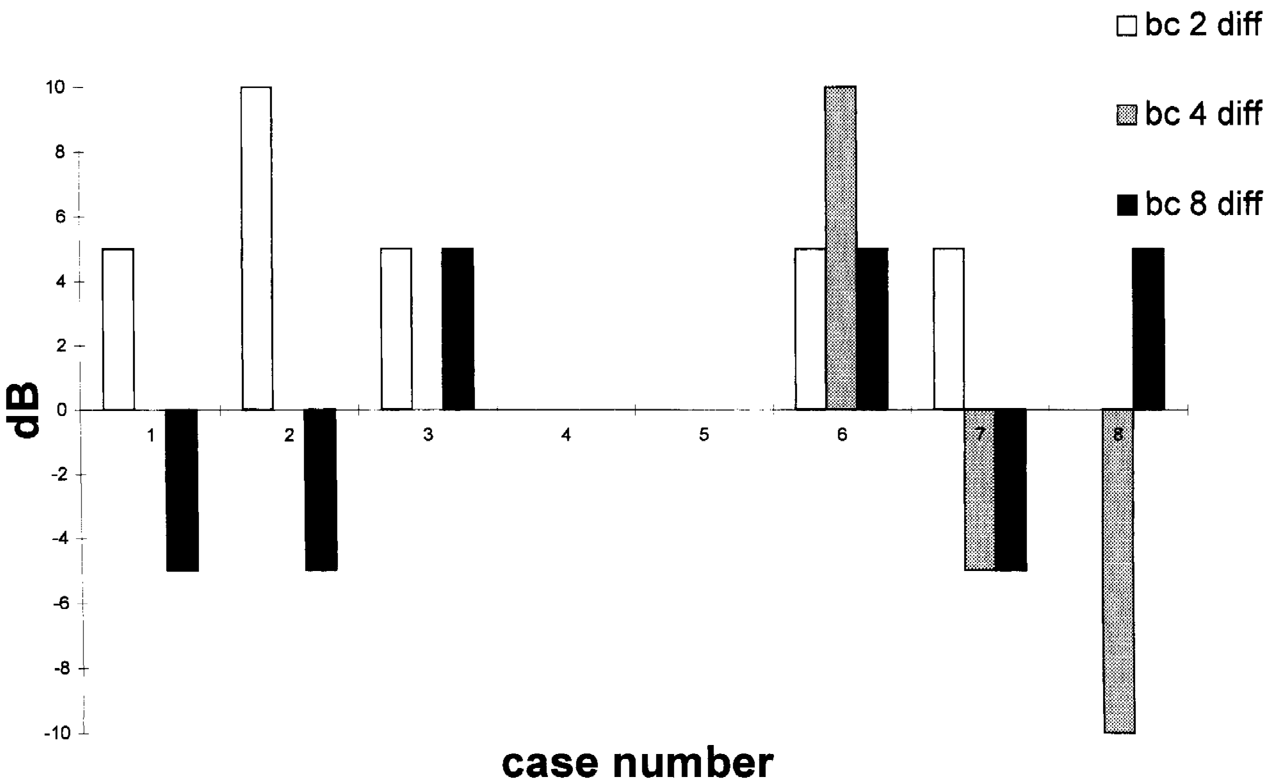

Fig. 4. Er:YAG laser-aided hyperostosis surgery of the external ear canal: Difference of the pre- and postoperative bone conduction threshold at 2, 4, and 8 kHz.

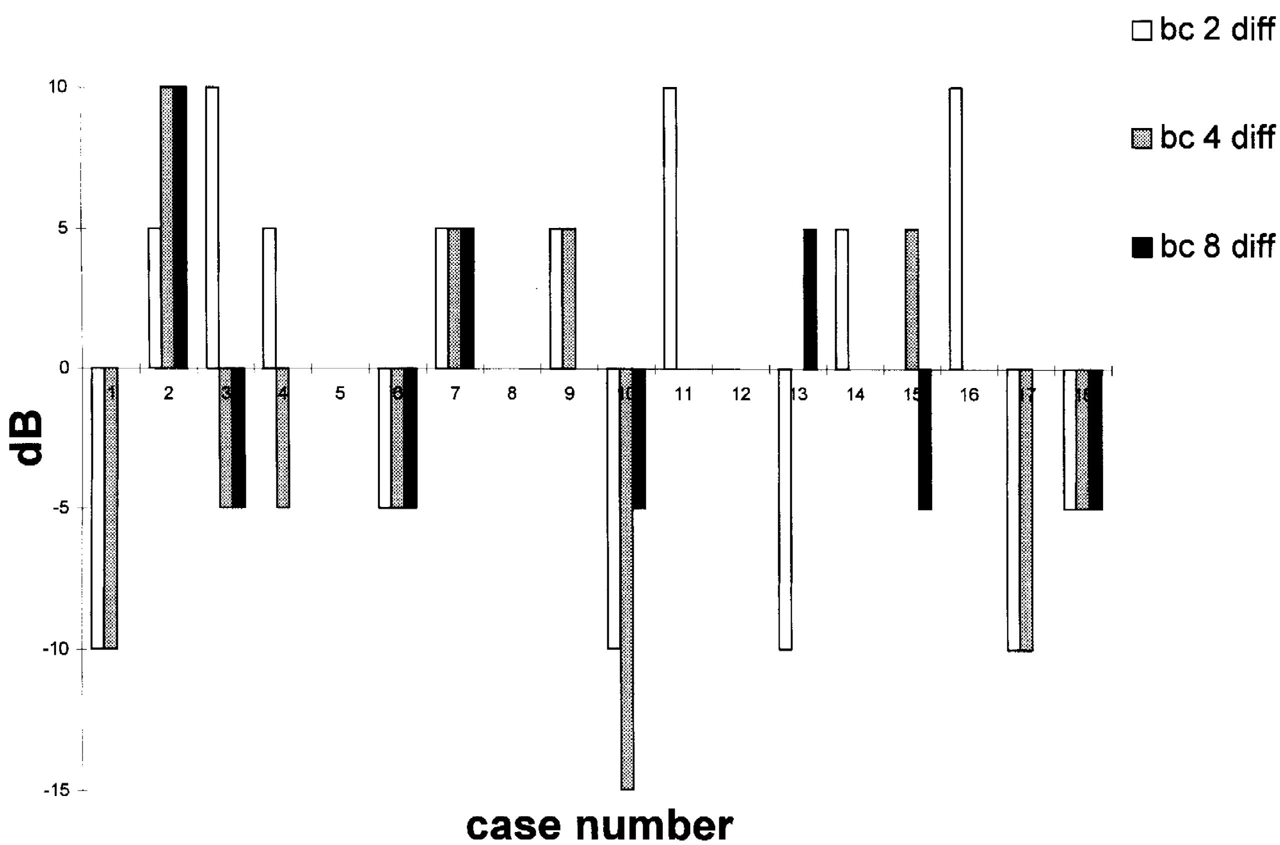

Fig. 5. Er:YAG laser aided surgery in cholesteatoma: Difference of the pre- and postoperative bone conduction threshold at 2, 4, and 8 kHz.

with any damage of hearing. It thus can be assumed that the resulting acoustic stress from 25 J of total laser dose is not sufficient to cause permanent damage of inner ear hearing, even though it was assumed that the noise level created by the laser pulses hitting the bone in the echo amplifying space of the auditory canal would impose additional stress on hearing because of the echo effect. Also, in no case did a patient complain of postoperative tinnitus.

Cholesteatoma. Eighteen patients with cholesteatoma were operated with the aid of the Er:YAG laser. In six cases, the postoperative audiogram showed a lowered bone conduction threshold of 5–10 dB at 4 kHz, the most sensitive frequency for inner ear damage. In 11 cases, the bone conduction threshold remained unchanged at 4 kHz or improved by 5–10 dB. In one case, the bone conduction threshold at 4 kHz fell significantly by 15 dB. Descriptive statistical evaluation showed no sign of any correlation of total applied laser dose and of change in bone conduction threshold at 4 kHz or any other tested frequencies (0.5, 1, 2, and 8 kHz).

DISCUSSION

This clinical study demonstrates for the first time the usefulness of Er:YAG lasers for different applications in ear surgery. To this end, different kinds of laser systems for micro operations have previously been employed by a variety of authors. Argon lasers have been applied by Perkins [7], Di Bartolomeo [8], McGee [9,10]. Their disadvantages were discussed by Gantz [11]. CO_2 lasers were used by Lesinski [12–15], KTP lasers were preferred by Silverstein et al. [16] and Thedinger [17]. Ho:YAG lasers [7,18] were also used. However, all these lasers lead to substantial heat transfer into adjacent areas, inducing carbonization and silication [19]. Also, insufficient depth control of such lasers has been criticized [15]. As a consequence, healing may become impaired or even impossible. One may speculate that this is the reason for the poor acceptance of such technologies in otology up to now.

The advantage of the Er:YAG laser lies in the fact that its wavelength is tuned to the maximum absorption peak of water. Therefore, this laser allows tissue removal without heat transfer to the operating site by induction of well-controllable micro explosions in the water-filled tissue matrix. As this effect is necessarily accompanied by clicking sounds near to the inner ear of the patient, the possibility of acoustic damage [20–23] had to be ruled out. This was done by performing equivalent operations in Guinea pigs [5], which are known to be some ten times more sensitive to acoustic traumata than humans [24] which showed no hearing loss for Er:YAG laser doses below 25,000 mJ. Therefore, this dose was defined as the maximum acceptable dose for ear operations and which is sufficient to remove bone tissue equivalent to the mass and size of the malleus or incus.

Hüttenbrink [25], summarizing the research results on middle ear mechanics, believes, like many other authors, that a direct and stable link from the tympanic membrane to the stapes (or footplate of the stapes) is best for sound conduction. The use of the Er:YAG laser allows the surgeon to make this stable link between the ossicles in a quasi osteosynthetic way. This was also demonstrated by Schlenk [26] on a temporal bone model from cadavers.

The results of the different operations in this study demonstrate: (1) that the Er:YAG laser can be used for drilling fine holes in auditory ossicles at high precision and ossicles can be shaped in situ with no systematic hearing damage, and (2) that stapedotomies can be performed with the Er:YAG laser without risk of hearing damage. However, more experience has to be gained in order to be able to assess the full potential and possible disadvantages of this novel and promising operation technique.

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